

The Role of Engineering in the Conservation of Architectural Heritage

Opening Lecture of the Resident National Member Mario Alberto CHIORINO
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The protection of architectural heritage requires the contribution of different sciences. This lecture discusses the significant and progressively increasing role of structural and geotechnical disciplines in the strategies for conservation and restoration of historical constructions and monumental buildings. Attention is paid to the gradually increasing recognition of the importance of this role within international debate¹, and corresponding reflection in principles and guidelines successively incorporated in charters and documents formulated at national and international level. A process that was accentuated in recent years, in connection in particular with the perspective of establishing scientifically based global strategies for the evaluation and mitigation of the seismic risk of some of the most relevant architectural heritage patrimonies located in seismic active areas, as e.g. Italy and India².

In its second part the lecture is focused on a few relevant case studies apt to demonstrate how these disciplines can effectively contribute to the processes of reliability analyses and of conservation of structurally complex and challenging important monuments of both historical and contemporary architecture.

¹ D.F. D'Ayala, M. Forsyth, *What is Conservation Engineering?*, in M. Forsyth (ed.), *Structures & Construction in Historic Building Conservation*, Wiley-Blackwell, Oxford 2007.

² R. Cecchi, M. Calvi (coords.), S. Lagomarsino (ed.), *Linee Guida per la valutazione e riduzione del rischio sismico del patrimonio culturale con riferimento alle Norme Tecniche per le Costruzioni* (Guidelines for the evaluation and reduction of seismic risk to cultural heritage with reference to the Technical Code for Constructions; in Italian), July 2006; 1st official edition: Dirett. Pres. Cons. Min. 12.10.2007, Gazzetta Ufficiale 29.01.2008 n. 24; 2nd official edition: Dirett. Pres. Cons. Min. 09.02.2011, Gazzetta Ufficiale 26.02.2011, n. 47, Supplemento ordinario n. 54. EU-India Economic Cross Cultural Programme: Improving the Seismic Resistance of Cultural Heritage Buildings, *Guidelines for the Conservation of Historical Masonry Structures in Seismic Areas*, Universidade do Minho, Universidad Polit cnica de Catalunya, Central Building Research Institute (India), Universit  di Padova, 2006.

A special attention is dedicated in the end to the case study of the Sanctuary of Vicoforte, a monumental building of great historical, architectural, and structural significance, characterized by one of the largest masonry domes in the world, and by far the largest oval one. Mention is made of the strategies adopted for structural modelling and analyses in the static domain (for the reliability assessments under gravity loads) as well as for the analyses in the dynamic domain (for both model updating processes and the evaluation of the seismic risk) of this outstanding historical construction, and of the related research program coordinated by the Politecnico di Torino in the context of a wide international debate and cooperation.

1. Historical aspects

Roots and early development of the contribution of mechanical and engineering sciences to conservation and restoration of historical monuments can be detected in the entire construction history of past centuries. A detailed review of this intriguing and exciting itinerary falls beyond the limits of this lecture; reference can be made to specialized literature in the history of mechanics and construction science³. One preeminent episode was the early application, although with some errors and limits, of the kinematic and the static approach of modern limit analysis to the checks of the safety conditions of St. Peter's dome in Rome, by, respectively, the Three Mathematicians⁴ (Fig. 1) and by

³ See e.g. E. Benvenuto, *La scienza delle costruzioni e il suo sviluppo storico* (Structural mechanics and its historical development; in Italian), Sansoni, Firenze 1981.

⁴ T. Le Seur, F. Jacquier, R.G. Boscovich, *Parere di tre matematici sopra i danni che si sono trovati nella cupola di S. Pietro, Sul fine dell'Anno 1742, dato per ordine di Nostro Signore Benedetto XIV* (Opinion of three mathematicians on the damages observed in St. Peter's dome at the end of the year 1742, given by order of Our Lord Benedict XIV; in Italian), Fratelli Palearini, Rome. Also in: *Scritture concernenti i danni della cupola di San Pietro di Roma e i loro rimedi* (Writings on the damages of St. Peter's dome and related remedial measures; in Italian), Occhi, Venezia 1742. T. Le Seur, F. Jacquier, R.G. Boscovich, *Riflessioni de' padri Tommaso Le Seur, Francesco Jacquier dell'Ordine de' Minimi, e Ruggiero Giuseppe Boscovich della Compagnia di Gesù, sopra alcune difficoltà spettanti i danni, e Risarcimenti della Cupola di S. Pietro Proposte nella Congregazione tenutasi nel Quirinale a' 20 Gennaro MDCCXLIII. E sopra alcune nuove Isppezioni fatte dopo la medesima Congregazione* (Reflections of ... on some difficulties concerning damages and remedial actions in St. Peter's dome presented in the Congregation held at the Quirinale on January 20th 1743. And on some new surveys made after the same congregation; in Italian), Rome 1743.

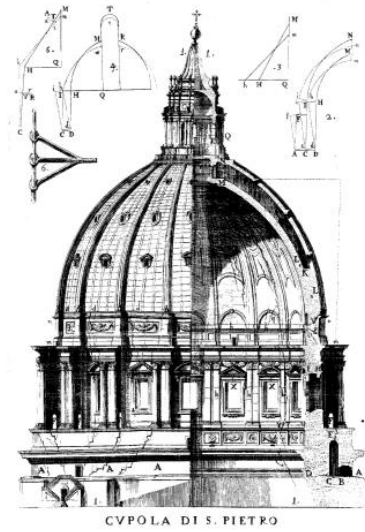


Fig. 1. Kinematic analysis of St. Peter's dome by the Three Mathematicians.

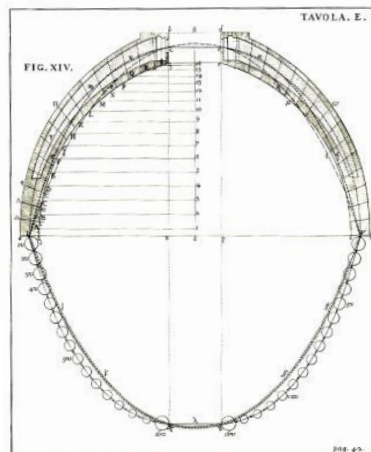


Fig. 2. Static analysis of St. Peter's dome by the Giovanni Poleni.

Poleni⁵ (Fig. 2), preliminary and in parallel to the strengthening intervention operated by Poleni and Vanvitelli in 1743-48⁶.

2. Principles and guidelines gradually incorporated in charters and documents

In a search for a more recent historical perspective of the progressively rising interaction and mutual fertilization between, on one side, the art, culture and science of conservation and restoration and, on the other side, the engineering sciences and techniques, in the frame of a broad vision of the polytechnic culture, one can first explore basic principles and conceptual guidance rules that were debated at the turn of 19th century in the national and international ambient of congresses and societies of architects and engineers.

⁵ G. Poleni, *Memorie istoriche della gran cupola del Tempio Vaticano, e de' i danni di essa, e de' ristoramenti loro, divise in libri cinque, alla Santità di Nostro Signore Papa Benedetto XIV* (Historical notes on the large dome of Vatican Temple, and on its damages, and their restoration, subdivided in five books, to the Holiness of Our Lord Benedict XIV; in Italian), Stamperia del Seminario, Padova 1748.

⁶ In what concerns the kinematic approach adopted by the Three Mathematicians it must be noted that an analysis varying the position of the mechanical hinges so that the minimum safety coefficient is found was not performed, the location of the hinges having being selected in pre-determined positions. Their approach and the consequent results have been analyzed and discussed in a wide number of studies in recent times, while recognizing however in any case the valuable conclusion of their report concerning the need of additional iron rings to guarantee the stability of the dome. For a comprehensive analysis of this wide debate see D. Capecchi, C. Tocci, *Le perizie sulla cupola vaticana di Le Seur, Jacques e Boscovich*, in «Palladio. Rivista di Storia dell'Architettura e Restauro», 47, 2011. See also: M.F. Funari, L.C. Silva, D.V. Oliveira, P.B. Lourenço, *A user-friendly digital tool for the structural assessment of historic domes: the case study of Saint Peter in Rome*, 12th International Conference on Structural Analysis of Historical Constructions SAHC 2020, P. Roca, L. Pelà, C. Molins (Eds.), pp. 211-220. On the other hand, the approach by Poleni was based on an early application of the static theorem. The limit of Poleni's approach consisted in the fact that his analysis of the position of the thrust line was limited to the dome, and did not concern the global structural system of the dome and the drum. However, in spite of the reassuring results of his analysis, Poleni wisely adopted the suggestion of the Three Mathematicians of applying the additional reinforcing iron rings. Both approaches, by the Three mathematicians and Poleni were in the frame of a two dimensional plane problem schematically applied to a slice of the dome in the vertical plane, resulting from the assumption of the presence of two meridian cracks isolating the slice from the rest of the dome. More advanced modern spatial approaches are discussed e.g. in G. Ventura, M. Coppola, C. Calderini, M.A. Chiorino, *Three-Dimensional Limit Analysis of the Vicoforte Elliptical Dome*, in «Journal of Wind Engineering and Industrial Aerodynamics», 8:5, 2014, pp. 649-669.

As an example, the First Italian Restoration Charter developed – with the preeminent role of Italian architect Camillo Boito (1836-1914) – within the 3rd Congress of Italian Architects and Engineers in 1883⁷ after having established as basic principle the respect of authenticity of monuments of architectural heritage, takes into consideration the problems arising from the need of improving their structural reliability. At this respect, it recommends a proper strategy based on minimum interventions, and in case of necessary additions, on an easy possibility to distinguish them from the original parts.

The Athens Charter for the Restoration of Historic Monuments, adopted at the First International Congress of Architects and Technicians of Historic Monuments, Athens 1931⁸, represents the main document in this domain developed in the first half of 20th century, establishing basic principles and guidelines. In its main introductory resolutions it clearly states, for the first time, the principle that «modern techniques and materials may be used in restoration work», while recommending in subsequent item IV Restoration of Monuments a «judicious use of all the resources at the disposal of modern technique and more especially of reinforced concrete» (a somehow ambiguous and perhaps excessive evidence given to this new technique, whose use is expected today to be considered with proper caution, in particular when rehabilitation interventions are intended to reduce the seismic risk of masonry and stone constructions of historical architectural heritage, due to possible undesirable increases in mass and rigidity in some parts of these constructions⁹).

The Athens Charter also recommends at its item VI that «before any consolidation or partial restoration is undertaken, a thorough analysis should be made of the defects and the nature of the decay of these monuments», recognizing that each case needs to be treated individually: an anticipated recommendation of modern integrated approach and methodological consistency, which, as discussed in the sequel, currently specify an appropriate sequence of consecutive steps similar to those used in medicine¹⁰.

⁷ C. Boito (ed.), *Prima Carta Italiana del Restauro* (First Italian Charter for Restoration; in Italian), 3rd Congress of Italian Architects and Engineers, Rome 1883.

⁸ *Athens Charter for the Restoration of Historic Monuments*, adopted at the First International Congress of Architects and Technicians of Historic Monuments, Athens 1931. <http://www.icomos.org/en/resources/charters-and-texts>.

⁹ See references in note 2. At the time reinforced concrete was extensively used e.g. in the strengthening of the masonry structures of the Mole Antonelliana in Turin (designed by Alessandro Antonelli at the end of 19th century) by A. Pozzo and G. Albenga (1930-1939, lower part) and later by Albenga and A. Danusso (1950-1953, dome). C. Calderini, L.C. Pagnini, *The debate on the strengthening of two slender masonry structures in early XX century*, in «Journal of Wind Engineering and Industrial Aerodynamics», 147, 2015, pp. 302-319.

¹⁰ See ICOMOS CHARTER – *Principles for the Analysis, Conservation and Structural*

The Italian Charter of Restoration, established in 1932 by «Consiglio Superiore delle Antichità e Belle Arti»¹¹, is largely inspired by the Athens Charter of 1931. After having stated that «restoration [...] results from a combination of science, art and technique», the Charter recommends to pay the deepest attention to maintenance and rehabilitation works in order to re-establish proper strength and durability for the monuments. Further in the text the following other guiding criteria are recommended:

- «in what concerns the additions that will be required to obtain the strengthening [...] the criterion to be followed should be, besides that of limiting these interventions to the possible minimum, also that of conceiving them in the simplest possible way and in accordance with the original structural conception»;

- in the aim of improving structural safety and reliability of a monument «the most advanced modern techniques may be used, whenever the use of techniques similar to the ancient ones appears inadequate for this scope», and structural conservation procedures must be based on «strictly scientific approaches».

In the first decades of the second half of past century, the major cultural event, in the progressive development at the international level of advanced policies for conservation and restoration of cultural heritage, is represented by the 2nd International Congress of Restoration held in Venice in 1964¹², which gathered architects and technicians of historic monuments from all over the world. The main outputs of this congress were the establishment of ICOMOS International Council on Monuments and Sites¹³, and the drafting of the International Charter for the Conservation and Restoration of Monuments and Sites¹⁴.

In what concerns ICOMOS, it must be noted that its mission underlines the contribution of sciences to the conservation process, stating that «it is the

Restoration of Architectural Heritage, 2003 (see here Section 3), and EU-India, 2006, cit.

¹¹ *Carta Italiana del Restauro* (Italian Charter for Restoration; in Italian), Consiglio Superiore per le antichità e belle arti, 1932.

¹² ICOMOS International Council of Monuments and Sites – Conseil International des Monuments et des Sites, *Il monumento per l'uomo – Le monument pour l'homme – The monument for the man*, Records of the II International Congress of Restoration, Venezia, 25-31 maggio 1964, Marsilio Editori, Padova 1971.

¹³ *Resolution Concerning the Creation of an International Non-Governmental Organisation for Monuments and Sites*, 1964, in ICOMOS 1971, pp. LXXII- LXXIV.

¹⁴ *International Charter for the Conservation and Restoration of Monuments and Sites (The Venice Charter)*, 1964, in ICOMOS 1971, pp. LXIX-LXXII, <https://www.icomos.org/charters-and-doctrinal-texts/>.

only global non-government organisation of this kind, which is dedicated to promoting the application of theory, methodology, and scientific techniques to the conservation of the architectural and archaeological heritage»¹⁵.

As for the Venice Charter, Piero Gazzola, Chairman of the organizing committee of the Congress and principal author with Raymond Lemaire of the Charter, declares in the Foreword to the records of the congress that

above all, it is to be recognized that the most important positive result by far of this assembly has been the formulation of the international code for restoration: not simply a cultural episode but a text of historical importance [...]. In fact, from now on, the Charter of Venice will be in the entire world the official code in the field of the conservation of cultural properties¹⁶.

Reaffirming some of the principles already stated in previous charters¹⁷ the Venice Charter declares at its Article 2

The conservation and restoration of monuments must have recourse to all the sciences and techniques which can contribute to the study and safeguarding of the architectural heritage,

and at its Article 10

Where traditional techniques prove inadequate, the consolidation of a monument can be achieved by the use of any modern technique for conservation and construction, the efficacy of which has been shown by scientific data and proved by experience.

If we go through the ponderous volume of the proceedings of the Venice Congress¹⁸ we may notice that some of the debated subjects show the progressive increase of the influence of the role of structural engineering and geotechnics in the conservation of historical monuments. Just to quote a few, we may indicate the discussion on the reconstruction, repair and preservation of monuments at Skopje destroyed or heavily damaged by the catastrophic earthquake of July 1963; the use of advanced techniques like strengthening through the application

¹⁵ <http://www.icomos.org/en/>

¹⁶ P. Gazzola, *Foreword*, in ICOMOS 1971, pp. XXVII-XXX.

¹⁷ P. Gazzola, R. Pane, *Proposte per una Carta Internazionale del Restauro* (Proposal for an International Charter of Restoration; in Italian with English Summary), in ICOMOS 1971, pp. 14-19.

¹⁸ ICOMOS 1971.

of active prestressing by steel tendons in the restoration of structures of architectural heritage; the debated problem of the detecting of adequate solutions for improving the progressively worsening stability, at the time, of the leaning Tower of Pisa, and the related structural and geotechnical issues¹⁹.

3. ICOMOS-ISCARSAH Principles and Guidelines

A turning point in the establishment of a specific ambient for debating the role of structural and geotechnical disciplines in the restoration of architectural heritage was the founding in 1996 by ICOMOS of ISCARSAH, the International Scientific Committee on the Analysis and Restoration of Structures of Architectural Heritage, as a worldwide forum and network for all those involved in the field. After a few years of debate, ISCARSAH authored the ICOMOS Charter Principles for the Analysis, Conservation and Structural Restoration of Architectural Heritage, ratified by ICOMOS in 2003, which were followed by Guidelines to be used in tandem with the Principles as global recommendations in this domain²⁰.

These two fundamental documents still represent the main international reference for selecting proper strategies for conservation and structural restoration interventions. In the past decade they also represented the conceptual frame for the establishment by the scientific community of advanced guidance criteria and strategies, which are discussed in the sequel, for the more specific and increasingly relevant challenge of the evaluation and mitigation of the seismic risk to architectural heritage.

The main concepts incorporated in the ICOMOS Principles are the following:

- «Conservation, reinforcement and restoration of architectural heritage requires a multi-disciplinary approach»;
- «The peculiarity of heritage structures, with their complex history, requires the organisation of studies and analyses in steps that are similar to those used in medicine. Anamnesis, diagnosis, therapy and controls, corresponding respectively to the searches for significant data and information, individuation of the causes of damage and decay, choice of the remedial measures and control of the efficiency of the interventions».

¹⁹ C. Cestelli Guidi, *Prolegomeni al problema della stabilità della Torre di Pisa* (Prolegomena to the problem of stability of the Tower of Pisa; in Italian with English Summary), in ICOMOS 1971, pp. 506-512.

²⁰ ICOMOS-CHARTER 2003, cit.; for Guidelines work is still in progress, see: P. Roca, *The ISCARSAH Guidelines on the Analysis, Conservation and Structural Restoration of Architectural Heritage*, in P. Roca et al. (Eds.), 2020, cit. (see note 6); reference is made in the following to the 2003 draft edition.

With respect to diagnosis the Principles state that it «is based on historical, qualitative and quantitative approaches» and that the quantitative approach requires «material and structural tests, monitoring and structural analysis».

In what concerns remedial measures and controls, an articulated framework is indicated for a virtuous approach evidencing, among other aspects, the needs to «address root causes rather than symptoms», to base conservation and reinforcement measures on adequate «safety evaluation and an understanding of the significance of the structure», and to keep «intervention to the minimum to guarantee safety and durability with the least harm to heritage values».

It is also specified that «the choice between “traditional” and “innovative” techniques should be weighed up on a case-by-case basis and preference given to those that are least invasive and most compatible with heritage values, bearing in mind safety and durability requirements». And it is remarked that «at times the difficulty of evaluating the real safety levels and the possible benefits of interventions may suggest “an observational method”, i.e. an incremental approach, starting from a minimum level of intervention, with the possible subsequent adoption of a series of supplementary or corrective measures».

Finally, the Principles insist on the concepts of a) *reversibility*, recommending that «where possible, any measures adopted should be “reversible” so that they can be removed and replaced with more suitable measures when new knowledge is acquired. Where they are not completely reversible, interventions should not limit further interventions»; and b) *compatibility*, requiring that «the characteristics of materials used in restoration work (in particular new materials) and their compatibility with existing materials should be fully established».

The related Guidelines represent an extended organic global document intended to assist in establishing a rational approach and related proper strategies for the analysis, conservation and structural restoration of architectural heritage. The successive topics of: 1) General Criteria, 2) Acquisition of data: Information and Investigation, 3) The structural behaviour, 4) Diagnosis and safety evaluation, and 5) Structural damage, materials decay and remedial measures, are discussed in detail providing valuable guidance criteria. The crucial role of modern structural analysis is underlined in what concerns item 4), evidencing, among other aspects, that

The essence of the problem is the identification of meaningful models that adequately depict both the structure and the associated phenomena with all their complexity making it possible to apply the theories at our disposal.

A proper evidence to the important role of mathematical interpretative models, and to the currently fully recognized fundamental role of model identification and updating techniques as further and more precisely stated in the sequel of the text:

Mathematical models are the common tools used in structural analysis. Models describing the original structure, if appropriately calibrated, allow comparison of the theoretical damage produced by different kinds of action with the damage actually surveyed, providing a useful tool for identifying the causes of such damage. Mathematical models of both the damaged and the reinforced structure will help to evaluate present safety levels and to assess the benefits of proposed interventions.

4. Guidelines for evaluation and mitigation of seismic risk to cultural heritage

One major occasion for a more intense recognition of the role of structural engineering and geotechnics in the conservation of historical monuments has been provided by the development, especially in the last two decades, of extended debate at international level on conservation strategies for architectural heritage in seismic prone areas, and the consequent editing in recent years of relevant guidance documents in the field aimed to contribute to mitigate the risk associated with the seismic vulnerability of this heritage. Such actions were undertaken in particular in consideration of major losses suffered along past century and in the first years of the new century by extended portions and important masterpieces of architectural heritage in some regions characterized at the same time by the presence of outstanding multi-century patrimony of this heritage and significant seismic action, like, for example and especially, Italy and India (see the map of seismic risk in Italy in Fig. 3).

The Italian Code of cultural heritage and landscape²¹, edited in 2004, at its article 29, Conservation, already recognizes the basic strategic concept that «in the case of historical buildings situated in regions with a declared seismic risk, the restoration must include structural improvement», for the reduction of this risk.

In the wake of this new progressive awareness of the importance of preserving cultural heritage, with particular regards to historical constructions and monuments, from seismic risk, one important and valuable document resulting from intense interdisciplinary debate is represented by the Italian

²¹ *Codice dei beni culturali e del paesaggio, ai sensi dell'articolo 10 della legge 6 luglio 2002, n. 137* (Code for cultural heritage and landscape; in Italian), Decreto Legislativo 22 gennaio 2004, n. 42, Gazzetta Ufficiale 24.02.2004, n. 45, Supplemento ordinario n. 28 (see also further amendments 2004-2011).

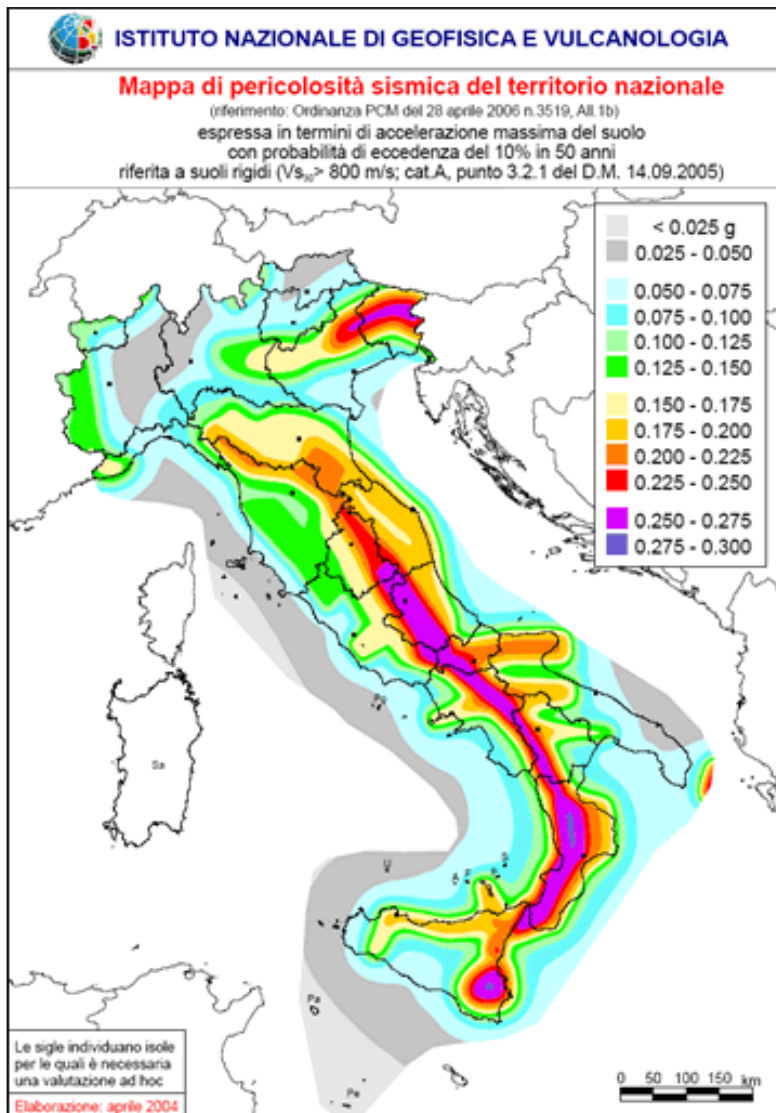


Fig. 3. Map of seismic risk in Italy. INGV Istituto Nazionale di Geofisica e Vulcanologia (2004). <http://zonesismiche.mi.ingv.it/>.

For any further information see INGV Site Guide: <http://terremoti.ingv.it/en/help>.

Guidelines for evaluation and mitigation of seismic risk to cultural heritage²². Drafted by a panel of academic and professional experts of, on one side, the art and science of restoration, and, on the other side, structural and geotechnical engineering, these Guidelines were first established in 2006, and subsequently reedited and updated in agreement with development and progressive evolution of the national Technical Code for constructions and inherent prescriptions on analyses and safety and reliability checks with respect to seismic actions.

At the international level, an important reference document is represented by the coeval Guidelines for the Conservation of Historical Masonry Structures in Seismic Areas, published in 2006 in the frame of EU-India Economic Cross Cultural Programme²³, together with two other guidance documents on, respectively, monitoring and strengthening strategies.

More recently, at the European level, the text of the European Guidelines for the seismic preservation of cultural heritage assets was delivered within the research project PERPETUATE (Performance-based approach to the earthquake protection of cultural heritage in European and Mediterranean countries) supported by the European Commission²⁴. The parallel research project NIKER (New integrated knowledge-based approaches to the protection of cultural heritage from earthquake-induced risk), also funded by the European Commission, aims at developing an integrated methodology for the systemic improvement of the seismic behaviour of cultural heritage assets²⁵.

²² See reference in note 2.

²³ See reference in note 2.

²⁴ C. Modena, S. Lagomarsino, F. da Porto, S. Cattari, *Earthquake protection of masonry historical constructions: overview of results from Niker and Perpetuate European projects*, in J. Jasieński (ed.) *SAHC 2012, 8th International Conference on Structural Analysis of Historical Constructions*, Wrocław, Poland, October 15-17, 2012, DWE, Wrocław 2012, pp. 2851-2860; S. Lagomarsino, S. Cattari, C. Calderini, *Deliverable D41, European Guidelines for the seismic preservation of cultural heritage assets*, in PERPETUATE, 2012; file:///C:/Users/Utente/Downloads/perpetuate-deliverable-d41-european-.pdf. See also <https://cordis.europa.eu/project/id/244229>; D.F. D'Ayala, S. Lagomarsino, *Performance-based assessment of cultural heritage assets: outcomes of the European FP7 PERPETUATE project*, in «Bulletin of Earthquake Engineering», Vol. 13, Issue 1, January 2015, pp. 5-12; S. Lagomarsino, S. Cattari, *PERPETUATE guidelines for seismic performance-based assessment of cultural heritage masonry structures*, in «Bulletin of Earthquake Engineering», Vol. 13, Issue 1, January 2015, pp. 13-47.

²⁵ C. Modena, S. Lagomarsino, F. da Porto, S. Cattari, *Earthquake protection of masonry historical constructions*, cit.; F. da Porto, B. Silva, F. Lorenzoni, P. Girardello, M.R. Valluzzi, C. Modena, *New integrated knowledge based approaches to the protection of cultural heritage from earthquake-induced risk*, in «Structural Engineering World Congress SEWC 2011», Villa Erba, Italy 2011, April 4-6. See also <https://cordis.europa.eu/project/id/244123/it>.

A detailed examination of the contents of all the above documents is out of the scope of this lecture. Suffice to say that, combining the most advanced outputs of current research in the fields of seismic engineering and of structural mechanics (with special regards to traditional construction techniques and materials, like e.g. stone and brick masonry and wood²⁶) with the requirements of conservation and restoration, pursuing the complex and debated target of reconciling safety and conservation requirements, the guidance concepts and criteria developed in all these documents address the following sequential aspects: the definition of performance limit states specific for the cultural heritage assets, the definition of the seismic input with proper attention to site amplification effects, the knowledge of the historical construction under consideration, the techniques for the analysis of the seismic response and evaluation of seismic safety through adequate modelling and, lastly, the definition of proper strategies for rehabilitation.

In what concerns structural models for the evaluation of seismic safety, besides discussing both different possible approaches for seismic analysis methods and seismic assessment levels, attention is dedicated, in particular by Italian Guidelines, to simplified evaluation models by structural types. These models are apt for a first level qualitative analysis for seismic safety assessment of the entire architectural heritage at a regional scale.

In consideration of the particular seismic vulnerability of the important architectural heritage represented in Italy by churches²⁷ (being characterized, especially in the case of monumental ones, by challenging structural architecture encompassing wide internal spaces, large arches and vaults, important façades with free standing tympanums, and, in quite a few cases, daring dome and drum configurations) a specific focus is placed on this type of structures. A certain number of typical damage mechanisms associated to various macro elements, which exhibit an almost independent behaviour, are presented in detail in the Italian Guidelines.

²⁶ While the ICOMOS and ISCARSAH Principles and Guidelines are referred to all types of historical structures of the architectural heritage, including modern buildings in iron, steel and reinforced concrete that are now recognised as being of historic importance, all other mentioned guidelines principally refer to historical masonry constructions.

²⁷ Surveys of vulnerability and damage assessment performed at regional levels after seismic events taking into consideration the entire heritage of both churches (including the simplest and less monumental) and of residential palaces show that in some cases the seismic vulnerability of palaces may result statistically higher, due to lack of maintenance, or improper rehabilitation and strengthening interventions by private owners. See S. Podestà, C. Romano, L. Scandolo, *Molise, Valutazione della sicurezza sismica a livello territoriale* (Molise, Evaluation of seismic safety at territorial level; in Italian); [https://www.beniculturali.it/mibac/multimedia/MiBAC/documents/1295445079370_4\)Esempi\(6\).pdf](https://www.beniculturali.it/mibac/multimedia/MiBAC/documents/1295445079370_4)Esempi(6).pdf).

In one of the recent above mentioned documents, PERPETUATE European Guidelines, a few advanced conceptual guidance criteria are accentuated²⁸:

The first driving idea is that the protection of cultural heritage needs an improvement in methods of analysis and assessment procedures rather than in intervention techniques. The second driving idea is that a verification approach in terms of displacement capacity rather than in term of strength is more reliable and effective for heritage buildings and that flexibility, ductility and lightness are positive factors for their seismic behaviour. The third idea is that a reliable assessment procedure of heritage buildings requires the assessment of both architectonic and artistic assets contained in them.

5. Advanced debate, research and education ambients

In the last two decades, an intense activity was developed at national and international level for the establishment of proper ambients for advanced debate, synthesis of research, and education on the role to be played by structural engineering and geotechnics in a multidisciplinary approach to the conservation of architectural heritage. One main forum for discussion of research achievements and for the analysis of notable case studies is represented by the series of SAHC international conferences on Structural Analysis of Historical Constructions. The first two editions were held in Barcelona in 1995 and 1998, followed by biennial editions in Europe and other locations in the world; the last recent venues were in 2018 in Cusco, Perú, and in 2021 in Barcelona (online edition coordinated by CIMNE International Centre for Numerical Methods in Engineering). The next edition will be in 2023 in Kyoto.

At the scientific literature level, one of the corresponding principal vehicles for research dissemination and debate in the field is currently represented by the International Journal of Architectural Heritage.

High level research and education multidisciplinary programs, merging advanced technical and scientific achievements in structural mechanics and geotechnics with the science, culture and ethics of conservation and restoration, have been established in various universities and academic institutions, in Italy and elsewhere, and within international networks of these institutions (see e.g. SAHC Advanced Masters in Structural Analysis of Monuments and

²⁸ PERPETUATE-Final Report Summary. <https://cordis.europa.eu/project/id/244229/reporting>.

Historical Constructions²⁹ and, in the more specific domain of protection of cultural heritage from earthquake-induced risk, the above mentioned European programs NIKER and PERPERTUATE).

6. Outstanding recent case studies emphasizing the role of structural engineering and geotechnics in the conservation of historical monuments

In recent years, a few outstanding cases of structural restoration interventions were successfully performed with a fundamental contribution of structural engineering and geotechnics, in the frame of an intentional multidisciplinary approach.

A most eminent case, among others, was the intervention, after a long historical debate³⁰, for the safeguard of the celebrated monument of the leaning Tower of Pisa.

An extraordinary and unique intervention that was based on the use of the most advanced scientific knowledge and techniques both in the field of geotechnics and structural mechanics, performed with the specific intent of adopting the less invasive approaches in the full respect of the historical artistic

²⁹ <http://www.msc-sahc.org/>

³⁰ A prominent protagonist of this debate in the second half of past century was Gustavo Colonnetti (1884-1986), the eminent scientist of mechanics of structures, former Professor at the Politecnico di Torino and President (1945-1956) of the Consiglio Nazionale delle Ricerche. In the 1960s Colonnetti was strongly worried by the problems of the increasing leaning and related stability problems of the Pisa Tower. Besides promoting a systematic monitoring campaign of the leaning of the Tower, he conceived some remedial interventions. Although his proposals of intervention consisting either in a device for lifting the tower in order to allow the construction of a new foundation (1963, with Riccardo Morandi, Fig. 4.1), or in a device based on the use of a lever pushed upward by a huge jack in order to reduce the stresses on the soil under the Tower foundation, and consequently the tendency to the increase of inclination (1965, Fig. 4.2) were debatable and probably utopian, the great merit of Colonnetti was to strongly raise the alert not only in the scientific ambient (see note 19 in Section 2), but also in the spheres of decision makers at the level of the public institutions. Colonnetti was also concerned by the effects of the wind on the Tower, and promoted an appropriate test of a 1:50 reduced scale model in the wind tunnel of the Politecnico di Torino. See G. Colonnetti, *Su la possibilità di sotto-fondazione del campanile di Pisa*, Commentarii, Pontificia Accademia Scientiarum, Vol. 1, n. 36, 1963; Id., *Progetto di sollevamento del campanile di Pisa onde rendere possibile la costruzione sotto di esso di una fondazione efficiente*, Stamperie Editoriali Rattero, Torino 1963; Id., *L'azione del vento sulla torre di Pisa e il problema della sua immediata salvaguardia*, in «Atti dell'Accademia delle Scienze», Vol. 99 (1964-1965), Torino, April 1965; Id., *Su la possibilità di arrestare il progressivo incremento della pendenza della torre di Pisa*, in «Atti dell'Accademia delle Scienze», Vol. 100 (1965-1966), Torino, November 1965.

and architectural values of the monument, and the ethics of restoration. Developed with a deep understanding of the strict connections in the risk of structural collapse of the Tower between progressive leaning, wind and seismic actions, and the existence of some critical sections in the masonry structure of the Tower due to inadequacy of the dimensions of the resisting sections, the final intervention – which was based on controlled ground extraction (under-excavation) from foundation layers, and active reversible intervention for local strengthening of the structure of the Tower, with the application of tensioned stainless steel reinforcing rings, after a thorough mechanical analysis and investigation of the structure (Fig. 5) – was the result not only of an intense debate but also, and especially, of a synthesis and integration between different cultures³¹.

Other outstanding cases of structural analysis, monitoring, and in some cases of strengthening and rehabilitation interventions, of important historical constructions are related to other celebrated monuments like, to quote just a few among many others, the Cathedral of Mexico City (where advanced monitoring and modeling was performed, with respect to soil settlements and seismic risk, and the under-excavation remedial measure, which was subsequently applied for the Pisa Tower, was first tested to counteract differential settlements³²); the dome of Santa Maria del Fiore in Florence for which a careful modeling and monitoring actions have been undertaken³³, as well as other notable monuments around the world.

³¹ S. Settis, M. D'Elia, M. Jamiolkowski, G. Macchi, F. Veniale, G. Viggiani (Eds.), *La Torre restituita. Gli studi e gli interventi che hanno consentito la stabilizzazione della Torre di Pisa* (The recovered Tower. Studies and interventions that have led to the stabilization of the Tower of Pisa; in Italian), Voll. I-III, Ist. Poligrafico e Zecca dello Stato, Coll. Bollettino d'Arte, Volume Speciale, Roma 2005; J.B. Burland, M.B. Jamiolkowski, N. Squeglia, C. Viggiani, *The Tower of Pisa. History, Construction and Geotechnical Stabilization*, CRC Press, London 2020, 62 pp.

³² R. Meli, A.R. Sánchez, *Rehabilitation of the Mexico City Cathedral*, in «Structural Engineering International», 9 (2), 1997, pp. 101-106; D. Rivera, R. Meli, R. Sánchez, B. Orozco, *Evaluation of the measured seismic response of the Mexico City Cathedral*, in «Earthquake Engineering & Structural Dynamics», Vol. 37, Issue 10, 2008, pp. 1249-1268; V. Hernández, E. Santoyo, J. Hernández, *Geotechnical behavior of the Cathedral after 10 years of the intervention of subsoil*, in F. Peña, M. Chávez (ed.), *Proceedings of SAHC 2014, 9th International Conference on Structural Analysis of Historical Constructions*, Mexico City, Mexico, 14-17, October 2014.

³³ G. Bartoli, M. Betti, C. Borri, *Numerical Modeling of the Structural Behavior of Brunelleschi's Dome of Santa Maria del Fiore*, in «International Journal of Architectural Heritage: Conservation, Analysis, and Restoration», Vol. 9, n. 4, 2015, pp. 408-429.

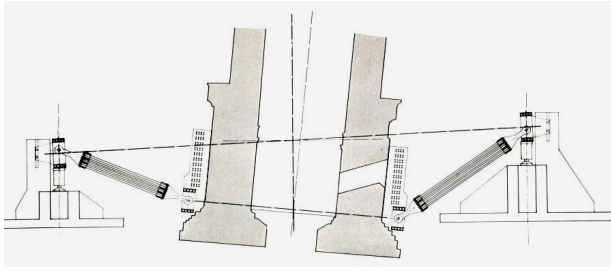


Fig. 4.1. Device for lifting the Tower in order to allow the construction of a new foundation (Gustavo Colonnetti with Riccardo Morandi, 1963).

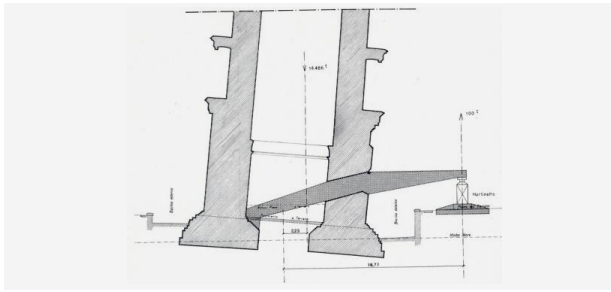


Fig. 4.2. Device for reducing the stresses on the soil under the Tower foundation (Gustavo Colonnetti, 1965).

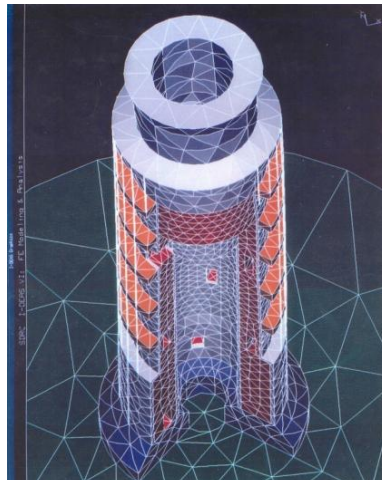


Fig. 5. Finite-element model for the structural analysis of the Tower of Pisa (G. Macchi in S. Settis *et al.*, 2005, cit.).

7. Some case studies concerning the conservation of the historical and contemporary architectural heritage in Turin

The architectural heritage of Turin is characterized by the presence of some important examples of baroque architecture, as well as, in recent times, by remarkable masterpieces of contemporary structural architecture.

Some case studies concerning the conservation of some notable works of art of this heritage are briefly discussed in the following.

Cappella della Sindone (Holy Shroud Chapel; Guarino Guarini 1679)

The conservation intervention concerned the strengthening and partial reconstruction of the Chapel after the destructive fire of 1997, and was completed in 2018 (Fig. 6). The project required an analysis of the initial concept of the complex structure made of brickwork and marble in the lower parts and of superimposed marble arches linked together by perimeter iron ties, with the addition of external masonry ribs, in the upper part of the dome. Perimeter iron cerclages are present at various lower levels. All iron ties of the upper part were strongly affected by the fire, which caused also the rupture of the perimeter cerclage crossing the main windows of the drum.

The structural analysis was performed on the basis of a refined finite-elements model (Fig. 7). The rehabilitation, besides the strengthening of the masonry and the connected marble artifacts, which were in large part replaced with new artifacts made of the same type of marble (as e.g. almost two thirds of the bearing columns and all side pilasters), included the substitution of the original iron ties in the upper part of the dome and of the cerclage at the windows level with new stainless steel ties including head anchoring systems allowing tension control and re-tensioning interventions. In addition, a circular tensioning ring made of stainless steel wires was added in the drum region to contain a perimeter crack in the vault of the small tunnel under the main windows, and two tensioned stainless steel rods were placed under the floor of the Chapel to connect the Chapel to the portico of the Royal Palace and the rigid walls of the Cathedral apse for seismic improvement³⁴.

³⁴ G. Macchi, «Per stupire gli intelletti e rendere gli spettatori atterriti». *Cappella guariniana della Sindone: analisi della concezione strutturale*, in «Memorie dell'Accademia delle Scienze di Torino. Classe di Scienze Fisiche, Matematiche e Naturali», Vol. 38-39 (2014-2015); P. Napoli, *Il consolidamento strutturale. Tecniche innovative e procedure di cantiere controllate per la restituzione delle resistenze*, «La Cappella della Sindone tra storia e restauro», Atti del Convegno Internazionale di Studi, a cura di M. Feroggio, SAGEPI, Genova, 2022, pp. 168-187. Main actors of project and control of works were G. and S. Macchi, V. Nascè, P. Napoli, W. Ceretto, G.C. Gonnet, *et al.*



Fig. 6. Cappella della Sindone (Holy Shroud Chapel). Original drawing by Guarini and internal view of the dome after restoration.

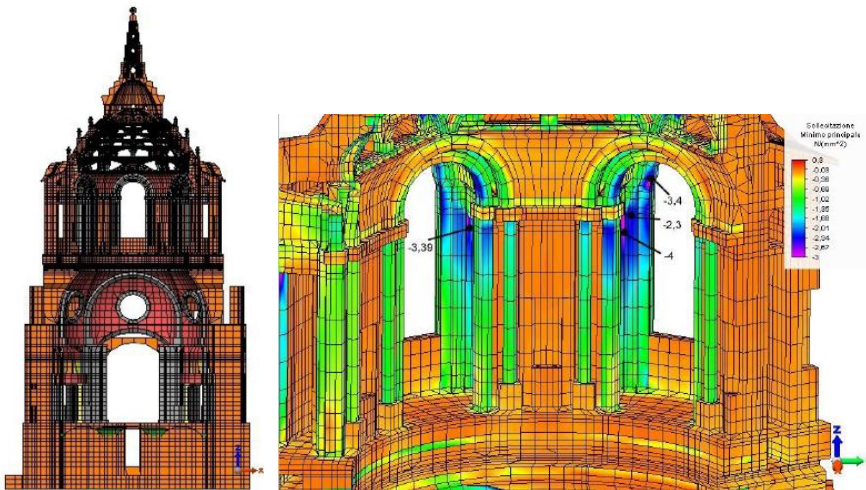


Fig. 7. Cappella della Sindone (Holy Shroud Chapel). Finite-element model for the structural analysis (left) and results of the analysis at the level of the windows of the dome (right). *Courtesy of Paolo Napoli.*

Collegio dei Nobili, then Palace of the Academy of Sciences and home of the Egyptian Museum

The Collegio dei Nobili was conceived by Jesuit Carlo Maurizio Vota under influence of Guarino Guarini (1624-83). Construction of the Palace was started in 1679 by Michelangelo Garove (1650-1713), most probably with a supervision by Guarini, under the patronage of Duchess of Savoia Maria Giovanna Battista (Fig. 8).

In 1773 the Savoia abolished the Jesuit order and as a consequence the College was closed in 1796. The left wing of the palace was given to the Academy of Sciences, founded in 1783. The main part of the building hosted museums and art galleries, with a prevailing presence of Egyptian art after the acquisition in 1824 of the Drovetti collection, which became the core of the Egyptian Museum currently occupying the whole part of the building, with the exception of the part pertaining to the Academy of Sciences.

Two major interventions of structural rehabilitation were performed in the last part of past century.

a) Strengthening of the columns of the atrium

The palace atrium is characterised by the presence of four very slender columns made of superimposed stone cylindrical elements of differing diameters. The two columns towards the courtyard are, according to a rather unusual scheme, located on the axis of the main inside wall which extends from the first floor to the top of the roof. In 1981 signs of static disorder were detected with the appearance of a localised break of the stone moulding of the base of one of the columns.

A careful load analysis showed high loads and stress values on the two columns incompatible with current safety criteria for structural elements of this type. A series of non-destructive tests carried out on the column elements using ultrasound equipment gave results that were characterised by notable dispersion, so that the presence of internal damage in the stone elements (initiation of cracks) could not be excluded. The combination of these results caused concern regarding the building's condition of stability, in consideration also of the use of the building as a museum open to the public, and led to the adoption of precautionary measures (provisional subsidiary steel support structure, Fig. 9) in preparation for strengthening of the columns.

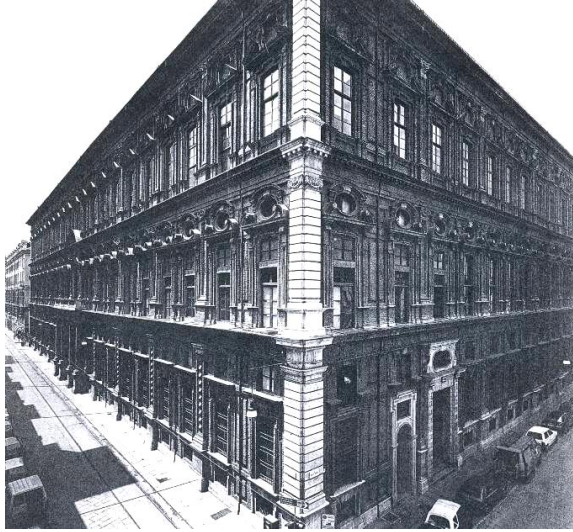


Fig. 8. Collegio dei Nobili, then Palace of the Academy of Sciences and home of the Egyptian Museum.

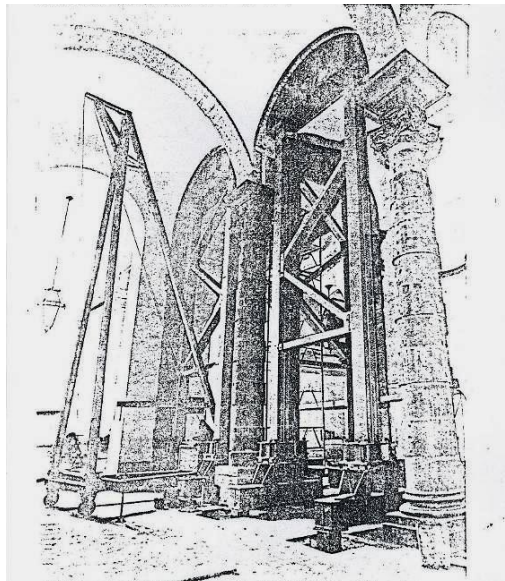


Fig. 9. Provisional subsidiary steel support structure.

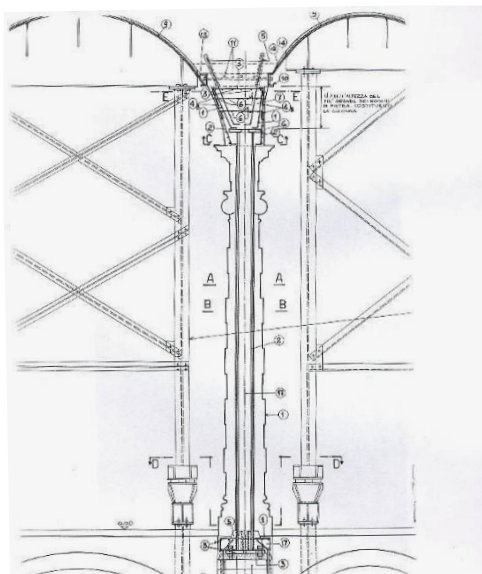


Fig. 10. The stone column reinforced with the insertion of the tubular steel column.

The definitive strengthening operation³⁵ (1990) consisted in the insertion of a tubular steel column, bearing the entire load, inside the two stone columns supporting the greatest loads (Fig. 10). The intervention required the removal of the original columns (after forcing the subsidiary structure with jacks placed at the base of its pillars, in order to remove the loads from the stone columns), the coring of their stone cylindrical elements before repositioning them around the steel columns.

The essential condition which was observed during the whole process was to always guarantee the palace safety and unrestrained access of the public to the museum collections, also during the delicate operations of definitive strengthening.

b) Architectural and structural renovation of the back wing of the Egyptian Museum (Ala Schiaparelli)

The project aim was to provide significant wider usable surfaces, for both exhibition purposes and the housing of administrative offices for the Egyptian

³⁵ The provisional subsidiary steel support structure, already conceived to allow the final strengthening intervention was designed by V. Nascé. The structural project for the final strengthening intervention (1986-1990) was redacted by Giulio Pizzetti, with the author and Giovanni Losana.

Museum, through the construction of two underground floors (which did not exist in the original building), the lower one for technical installations, and the addition within the building of one more floor aboveground.

In the essence only the two principal front and back masonry façades would be maintained.

The two main constraints were represented by 1) the presence at the ground floor of the Ellesija Temple³⁶, and 2) the fact that the back façade was founded on the foundations of the Roman walls of the ancient city *Augusta Taurinorum*, whose base is located at - 4.25 m with respect to the ground level, while excavations had to be undertaken until a depth of - 10.35 m.

The indications provided by the Superintendent of Cultural Heritage were a) the need to preserve the integrity of the Temple as originally reassembled, and b) the need to guarantee the conservation of both masonry façades, and, in particular, the integrity of the foundations of the Roman walls under the back façade.

With reference to these two aspects representing the main constraints of the structural rehabilitation intervention³⁷, the following strategies, among others, were established in the complex sequence of construction phases:

- use of a curtain of micropiles for the protection and support of the Roman walls foundations during the excavations, the curtain being subsequently incorporated in the new reinforced concrete structures, and of micropiles drilled through the Roman wall foundations for the support of the new reinforced concrete columns placed above the foundations,
- provisional lifting of the Ellesija Temple to allow the excavation process and the subsequent construction of the reinforced concrete structures of the ground floors,
- construction of four provisional wells for supporting the temple and the apparatus for its provisional lifting.

³⁶ The Ellesija Temple comes from Upper Egypt, south of Aswan along the Nile Valley now covered by the waters of Lake Nasser. It was taken in agreement with UNESCO and given in 1961 as a gift to the Egyptian Museum in Turin; other temples belonging to the same environment and different eras are now in New York, Leiden and Madrid. The temple was constructed by Tutmose III (18th Dynasty, New Kingdom, 1479-1425 BC) and renovated by Ramses II in 1250 BC. The temple was cut in pieces, transported to Turin and rebuilt in the ground floor (no underground floors were present at the date) of the back wing (Ala Schiaparelli) of the Museum.

³⁷ The project for the structural rehabilitation intervention (1987-1990) was redacted by Giulio Pizzetti and the author with Giovanni Losana, with the consultancy of Michele Jamiolkowski and IG Ingegneria Geotecnica Consulting Engineers for soil mechanics and foundations aspects. The procedures for the raising of the Ellesija temple were defined by Giorgio Garbaccio. Franco Levi acted as structural engineering consultant for the financing Institution.

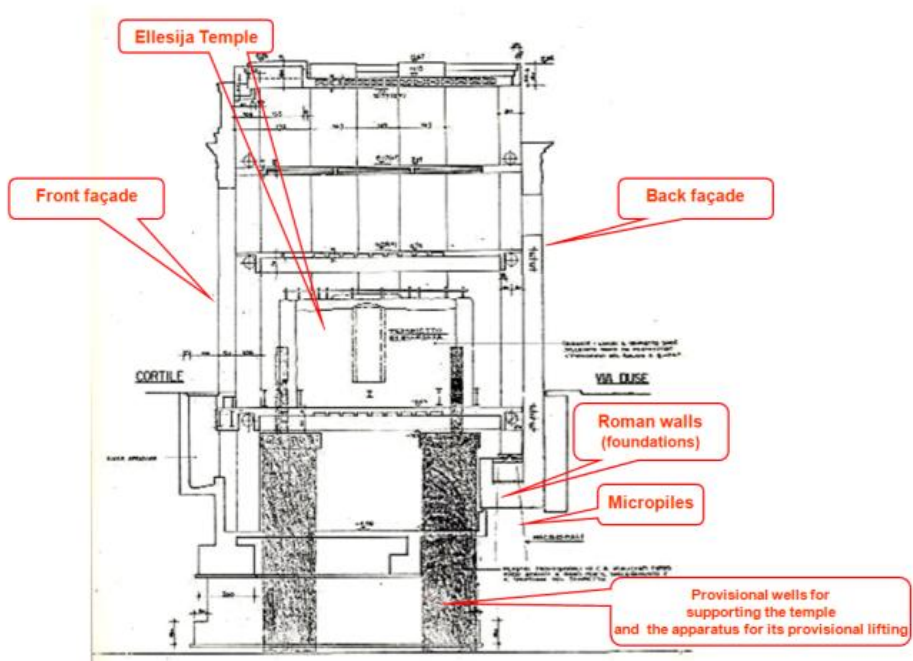


Fig. 11. Cross section of the Ala Schiaparelli with indication of the structural interventions.



Fig. 12. Front façade of the Ala Schiaparelli during the structural interventions.

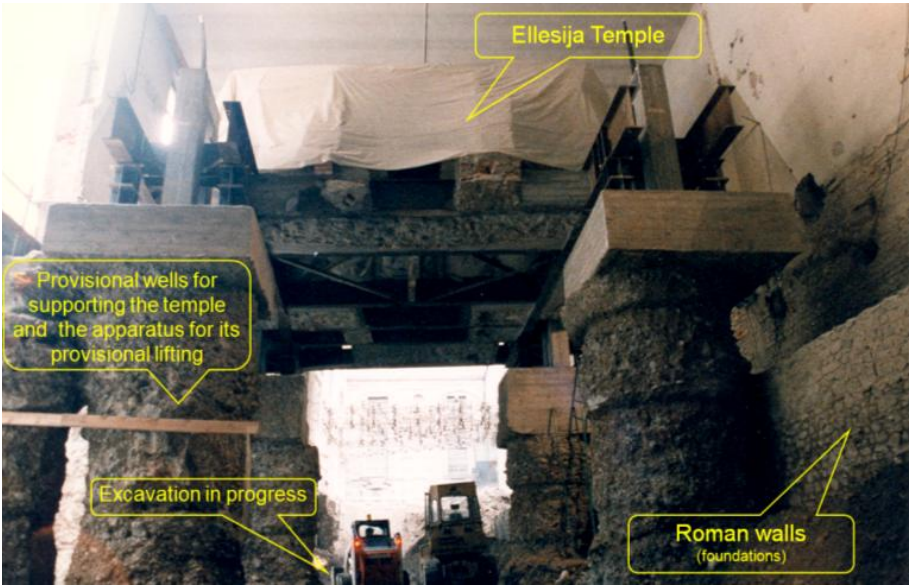


Fig. 13. Excavation under the Ellesija Temple.

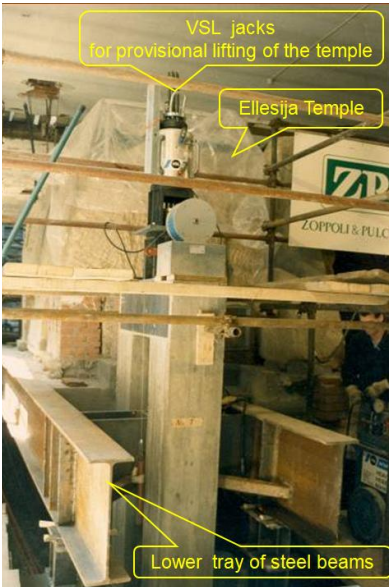


Fig. 14. The apparatus for the provisional lifting of Ellesija Temple.



Fig. 15. Ellesija Temple: final setting and interior decoration.

The apparatus for lifting the Temple consisted in a tray of steel beams placed underneath the Temple and raised through a system of vertical tendons and jacks placed on reinforced concrete pillars built on the top of the four provisional wells. The above complex strategies are documented in Figures 11 to 15.

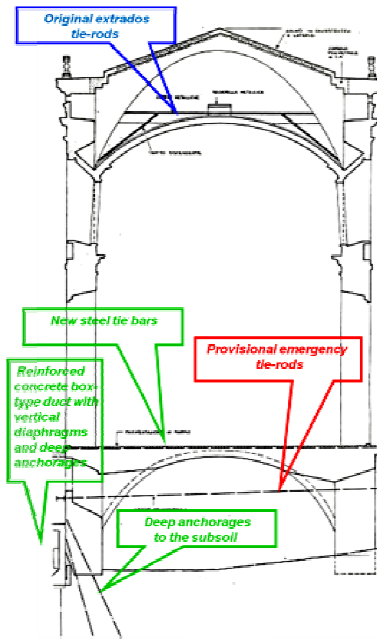
Royal Palace at Venaria Reale – Galleria di Diana (Filippo Juvarra 1716)

A last interesting case study of structural rehabilitation intervention in Turin baroque architectural heritage concerns a strengthening intervention in the Galleria di Diana built by Filippo Juvarra at the Royal Palace of Venaria Reale, one of the most ambitious royal palaces in the wide group of country residences of the Savoia dynasty around Turin (Fig. 16).

On the occasion of an excavation in the internal courtyard along the side of the Galleria for some preliminary retrofitting interventions and installation



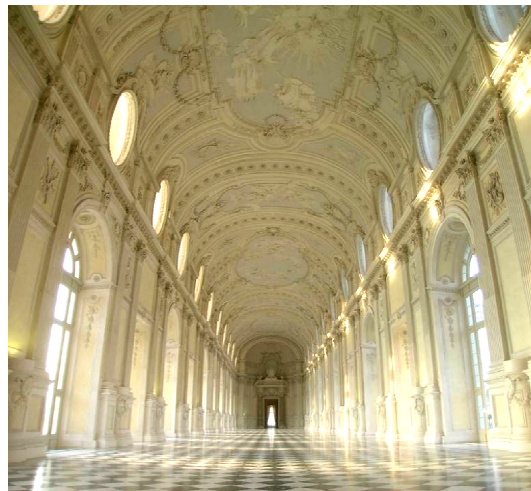
Fig. 16. Royal Palace at Venaria Reale. Main building by A. Castellamonte at the center and the Galleria di Diana at its right.



a



b



c

Fig. 17. Galleria di Diana at Venaria Reale; a: Original inverted tie-rods in the extrados of the vault (blue), Provisional emergency tie-rods (red), Final tie-bars and deep anchorages of the concrete duct to the subsoil (green); b: Placing of the final tie-bars in the floor of the Galleria; c: the Galleria after the structural rehabilitation intervention.

of an heating system, in 1986, for a reuse of the Palace which was at the time almost abandoned, an important longitudinal crack opened in the middle of the ground floor structure of the Galleria. This was due to the loss of the containment effect of lateral soil, and evidenced the low efficacy of the inverted tie-rods placed by Juvarra, for understandable aesthetical reasons, at the extradados of the upper vault of the Galleria.

The emergency intervention consisted in the provisional application of high strength steel tie-rods at the level of the underground floor. Finally permanent new high strength steel tie-bars were inserted in the floor of the Galleria and the reinforced concrete duct, supported by vertical diaphragms, which was built for the installations of the pipes of the heating system, was anchored to the underground soil with long tie-rods³⁸.

Turin Exhibition Center, Hall B (Pier Luigi Nervi, 1948-1954)

The Hall B of Turin Exhibition Center designed by the famous engineer and structural artist Pier Luigi Nervi (1891-1979) represents a celebrated masterpiece of contemporary structural architecture (Fig. 18)³⁹.

After years of abandon, a recent project of retrofitting and reuse for the Turin Civic Library is currently under way, in the frame of a wider program of recovery of the entire complex of the Exhibition Center⁴⁰. In this context a wide program of structural modelling and analyses and structural health monitoring of Hall B has been undertaken⁴¹, in order to explore the aspects of structural

³⁸ The project for the emergency intervention and the final structural rehabilitation (1986-1987) was redacted by Giulio Pizzetti and the author with Giovanni Losana, with the consultancy of Michele Jamiolkowski for soil mechanics and foundations aspects.

³⁹ C. Olmo, C. Chiorino (Eds.), *Pier Luigi Nervi. Architecture as Challenge*, Silvana Editoriale, Milan 2010; J.F. Abel, G. Arun, M.A. Chiorino, *Special Double Issue on Pier Luigi Nervi: Preface by the Guest Editors*, in «Journal of the IASS International Association for Shell and Spatial Structures», Vol. 54, No. 2 & 3, September 2013, pp. 79-86.

⁴⁰ The project was developed by Rafael Moneo, Isolarchitetti, ICIS S.r.l. (coordinator), Ing. G.B. Quirico, MCM Ingegneria, Onleco Srl, see: R. Ceravolo, C. Chiorino, M.A. Chiorino, A. Isola, S. Isola, E. Lenticchia, L. Luciani, R. Moneo (2018), *Preservation and rehabilitation strategies for the shell and spatial structures by Nervi and Morandi of the Turin Exhibition Center*, Proceedings of the IASS Symposium 2018, July 16-20, 2018, MIT, Boston, USA. In Fig. 18 the final edition of the project (2023) currently under completion.

⁴¹ E. Lenticchia, R. Ceravolo, P. Antonaci, *Sensor Placement Strategies for the Seismic Monitoring of Complex Vaulted Structures of the Modern Architectural Heritage*, Hindawi Shock and Vibration Vol. 2018; R. Ceravolo, G. De Lucia, E. Lenticchia, G. Miraglia, A. Quattrone, F. Tondolo, E. Matta, G. Sammartano, A. Spanò, C. Chiorino, G. Bruschi, P. Faccio, A. Nanni, *Challenges in the reuse and upgrade of Pier Luigi Nervi's structures*, 12th International Conference on Structural Analysis of Historical Constructions SAHC 2020, P. Roca, L. Pelà, C. Molins (Eds.), pp. 71-81.

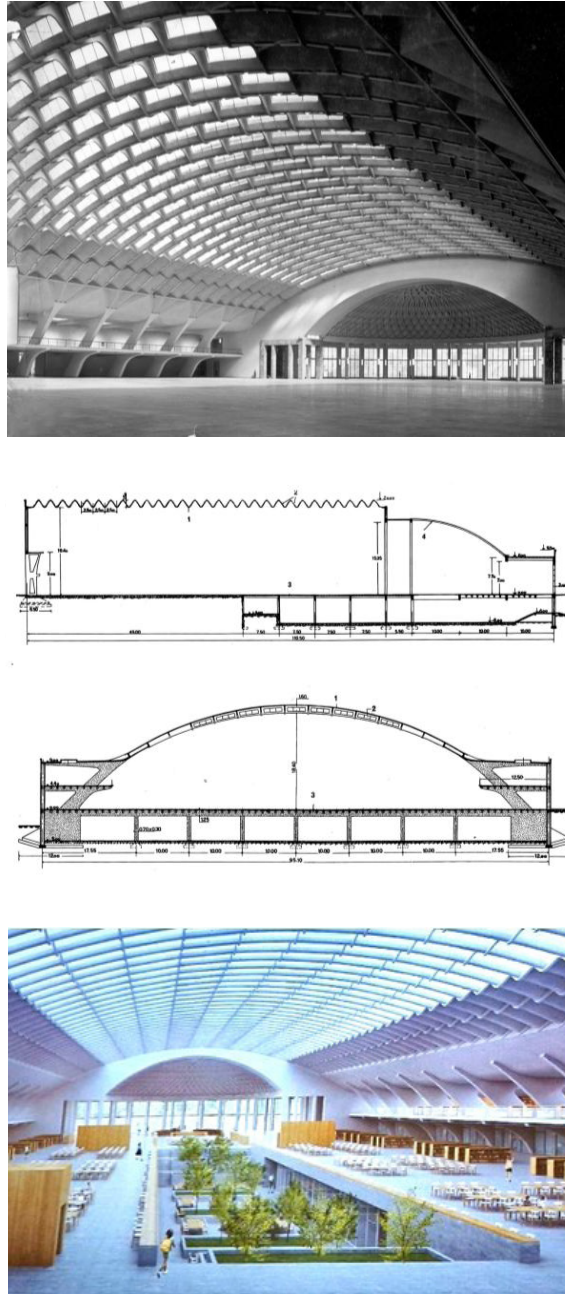
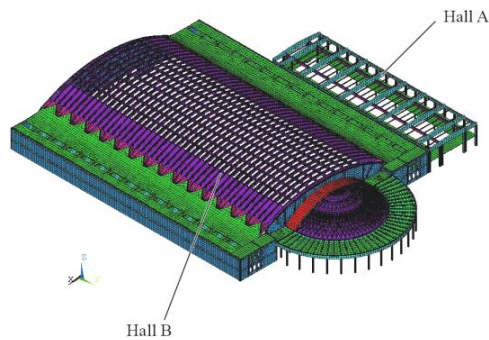
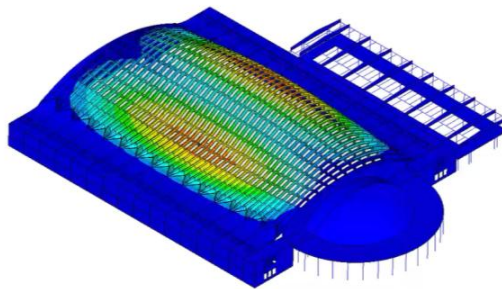


Fig. 18. Turin Exhibition Center, Hall B (Pier Luigi Nervi, 1948-1954). Internal view, longitudinal and transversal cross sections and reuse project (2023).



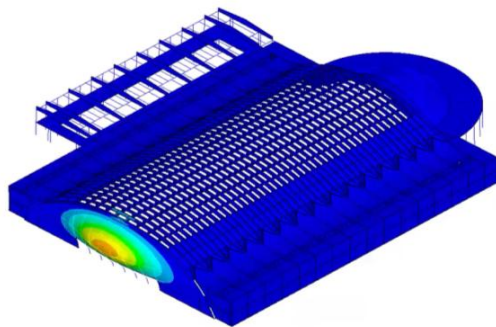
Finite-element model

```
NODAL SOLUTION
STEP=1
SUB =1
FREQ=1.76845
USUM      (AVG)
RSYS=0
DMX =.001267
SMX =.001267
```



First vibration mode

```
NODAL SOLUTION
STEP=1
SUB =5
FREQ=2.20335
USUM      (AVG)
RSYS=0
DMX =.002734
SMX =.002734
```



Fifth vibration mode

Fig. 19. Finite element model and vibration modes.

reliability and durability of this very special daring spatial architectural structure, shaped like a cathedral with a huge nave and an apse, characterized by a first application at large scale by Nervi of his innovative ferrocement construction system, and to establish a proper Conservation Plan⁴².

In what concerns structural reliability aspects attention is being paid in particular to the structural response to seismic actions (which were not considered in the original project of the Hall according to the technical standards at the time of its construction), in order to respond to the safety requirements of current guidelines, with special regard to the buildings used as public spaces, as in case of a library.

For this purpose a finite element model of the structure has been established, and some preliminary dynamic analyses have been performed (Fig. 19).

These analyses show that the principal vibration modes fall in the amplification zone of the seismic response spectrum. The most critical responses are those related to the undulated thin shell vault, the out-of-the-plane movements of the tympani and the presence of the apse, which cause an interaction with the main body of the hall. Also, the preliminary bending and shear checks show that most elements, in particular inclined pillars, are unsafe with respect to shear.

The dynamic analyses are also required to define an optimal sensor placement strategy (see note 41). When an adequate sensor placement will be performed useful information will be obtained for the updating of the numerical models of the structures.

Additionally, onsite inspections and non-destructive or partially destructive tests and laboratory tests for the evaluation of the material (concrete and steel) properties are currently being started and will provide further important information to improve the computational models and the evaluation of the structure performance, its residual service life, and the need and type of rehabilitation and upgrading interventions, with regard in particular to the seismic actions.

A special attention is being dedicated to the durability aspects in consideration of the very special characteristics of ferrocement construction system – widely used in the spatial structure of Hall B – characterized by very thin structural elements with a dense mesh of thin reinforcing bars and extremely thin concrete cover, while the concrete mortar is characterized by significantly high contents of cement.

The discussion of all these aspects goes beyond the scope of this lecture

⁴² The Conservation Plan for the structures by Nervi of both Hall B and the nearby smaller Hall C of Turin Exhibition Center has been awarded the Keeping It Modern 2019 Grant of the Getty Foundation, Los Angeles, USA.

and reference is made, besides the extremely wide literature and set of guideline documents referring to the conservation and strengthening of reinforced concrete in general⁴³, to some studies and guidelines specifically dedicated to the ferrocement⁴⁴.

In what concerns durability aspects of ferrocement, a recent research has been developed at the Northwestern University in USA in the frame of a graduation thesis of the Politecnico di Torino⁴⁵. In a brief synthesis it may be said that this research has been developed at the level of the nanoscale of the ferrocement material, and that the use of Tetraethyl Orthosilicate as protective material seems a promising option to improve the durability of ferrocement.

8. The case study of the Sanctuary of Vicoforte with its large oval dome

In this concluding part reference is made to a relevant case study concerning the contribution of structural engineering and geotechnics to the conservation of a prominent monument of the architectural heritage: the Basilica «Regina Montis Regalis», also known as Sanctuary of Vicoforte, located near Mondovì in the province of Cuneo in northwest Italy. The Basilica is a monument of great historical and architectural significance, owing its fame primarily to its big masonry oval dome (axes 37.15x24.50 m), the largest of this shape the world over, and one of the largest domes as a whole (Fig. 20)⁴⁶.

⁴³ See e.g. the extended list of guidelines developed at the European level of CEN, the European Committee for Standardization, by CEN/TC 104 – *Concrete and related products: CEN/TC 104 EN 1504 – Products and systems for the protection and repair of concrete structures – Definitions, requirements, quality control and evaluation of conformity* – Part 1 to 10, 2004-2017. See also the technical and guidance documents published by *fib* International Federation for Structural Concrete and ACI American Concrete Institute. In recent years a wide use of composite materials has been adopted for the strengthening of reinforced concrete constructions, and in particular for their upgrading to resist to seismic actions, and an extended literature and guidance documents have been published e.g. by *fib* and ACI. For a brief overview of these composite materials see e.g.: L. Coppola and A. Buoso, *I materiali compositi per il rinforzo statico e l'adeguamento sismico delle strutture in cemento armato (Composite materials for structural rehabilitation and upgrading with regard to the seismic actions)*, Section 8.6 (pp. 202-212) in *Il Restauro dell'Architettura Moderna in Cemento Armato* (Restoration of Modern Architecture in Reinforced Concrete; in Italian), Hoepli, Milan 2015.

⁴⁴ ACI 549R-18. *Report on Ferrocement*, ACI American Concrete Institute 2018; ACI 549.1R-18: *Design Guide for Ferrocement*, ACI American Concrete Institute 2018.

⁴⁵ A. D'Alessandro, D.J. Corr, S.P. Shah, *Use of Tetraethyl Orthosilicate to Improve Durability of Ferrocement*, in «ACI Materials Journal», Vol. 116, N° 6, November 2019.

⁴⁶ M.A. Chiorino, A. Spadafora, C. Calderini, S. Lagomarsino, *Modeling strategies for the*

Since the earliest stages of construction, started in 1596 on the basis of a project by architect Ascanio Vittozzi (1583-1615), the large and massive oval building of the Basilica was adversely affected by important absolute and differential settlements of foundations, due to an unfortunate selection of the site, which is characterized by an inclined (from east-northeast to west-southwest) marlstone bed-rock surmounted by soft clay-silt layers of increasing depth (only in the north-east part the foundations of the Basilica reach the marl bed-rock; see Fig. 21 left). Construction was slowed down and almost stopped along the 17th century, while in the early 18th century works were resumed and entrusted to architect Francesco Gallo (1672-1750), who demolished the previously built part of the drum, levelled its base, and erected a new slender and transparent drum with closely spaced window openings. The construction of the slender baroque slightly ribbed masonry dome, with wide round openings at its base and contained by a system of circular iron tension rings located within the masonry at three different levels in this same region, was started in 1731 and the Basilica was inaugurated in 1735 on the completion of the lantern top⁴⁷.

The dome-drum system suffered since the beginning from significant structural problems, related in part to the additional settlements induced by the new built masses, and, to a large extent, to the daring structural configuration of the system itself. During the years following the construction stage an extended system of wide cracks developed along the meridians of the dome and the drum (Fig. 21 right), progressively transforming the structural system into an ensemble, typical of these masonry architectural configurations, of slender masonry slices, separated by meridian planes and converging to the top of the dome. The significant lateral thrusts exerted by these approximately arch shaped structural elements, insufficiently opposed by the iron tension rings, was evidenced by significant shear-type diagonal cracks in the vertical walls of the eight slender buttressing vertical elements located at the perimeter of the drum and the dome, part of them incorporating the ascending stairs.

In 1983, concerns over these severe settlement and cracking phenomena affecting the structure prompted the decision to undertake inspection, monitoring, and strengthening interventions. After a survey and investigation campaign designed to acquire detailed data on the conditions of the foundations, the geo-technical aspects of the site, the mechanical parameters of the masonry, the crack

world's largest elliptical dome at Vicoforte, in «International Journal of Architectural Heritage: Conservation, Analysis, and Restoration», Vol. 2, N° 3, July-September 2008, pp. 274-303. As the geometry of the horizontal section of the dome is similar to, but does not correspond exactly to an ellipse, it was recently decided to normally refer to it as an oval dome.

⁴⁷ G. Vacchetta, *Nuova storia artistica del Santuario della Madonna di Mondovì a Vico* (New artistic history of the Sanctuary of the Virgin of Mondovì at Vico; in Italian), Società per gli Studi Storici Archeologici ed Artistici della Provincia di Cuneo, 1984.

widths and distribution, and the geometry of the dome and of the monument as a whole, a strengthening system was put in place (1985–1987). It consisted of 56 active high strength steel tie-bars placed within holes drilled in the masonry at the top of the drum along 14 tangents around the perimeter, and slightly tensioned by jacks. The 14 segments of this perimeter strengthening system are connected each other by steel frames. A monitoring system was set up to survey crack propagation, deformations of the structure as well as stresses in the tie-bars (re-tensioned in 1997)⁴⁸. Although the strengthening intervention was of an undoubtedly invasive type, proper design choices were adopted to conceal its structural components. From the structural point of view, the intervention proved to be effective to contain lateral thrusts and to govern the tendency of cracks to further expand.

Along the last more than one decade a new intense survey, investigation and research program was established on the geometry of the construction, its constitutive aspects, the physic-mechanical characteristics of the materials, and the modelling and analysis of the structural responses in the static domain under the action of gravity loads and foundation settlements.

In addition, concerns about the safety of the monument with respect to seismic events – in the context of the new strategies discussed in the previous sections for the evaluation and mitigation of seismic risk to architectural heritage developed at national and international level – prompted the decision to develop a new wide scope investigation program. This was done in the frame of an agreement with Italian Ministry for Cultural Heritage aimed at testing the practicality of the specific Italian Guidelines on this subject⁴⁹ in the case of outstanding monuments, selecting the Basilica at Vicoforte as a case study for this evaluation.

The results, at the date, of the program are documented in detail in an extended series of papers⁵⁰ and briefly summarized in the following.

⁴⁸ M.A. Chiorino, A. Spadafora, C. Calderini, S. Lagomarsino, *Modeling strategies for the world's largest elliptical dome at Vicoforte*, cit.

⁴⁹ See reference in note 2. See also Section 4.

⁵⁰ See among others: M.A. Chiorino, A. Spadafora, C. Calderini, S. Lagomarsino, *Modeling strategies for the world's largest elliptical dome at Vicoforte*, cit.; C.G. Lai, M. Corigliano, H. Sánchez, L. Scandella, *Definition of seismic input at the «Regina Montis Regalis» Basilica of Vicoforte, Northern Italy*, IUSS Press Pavia 2009; L. Scandella, C.G. Lai, D. Spallarossa, M. Corigliano, *Ground shaking scenarios at the town of Vicoforte, Italy*, in «Soil Dynamics and Earthquake Engineering», 31, 2011, pp. 757-772; M.A. Chiorino, R. Ceravolo, A. Spadafora, L. Zanotti Fragonara, G. Abbiati, *Dynamic Characterization of Complex Masonry Structures: The Sanctuary of Vicoforte*, in «International Journal of Architectural Heritage: Conservation, Analysis, and Restoration», Vol. 5, N° 3, 2011, pp. 296-314; M.A. Chiorino, C. Casalegno, *Survey and structural modeling for the reliability assessment of the world's largest elliptical dome at Vicoforte, Keynote lecture*, Proceedings of «Domes in the World». International Congress, Florence, Italy, March 19-23, 2012, CD; M.A. Chiorino, R. Ceravolo, C.G. Lai, C. Casalegno, *Survey, seismic*



Fig. 20 (left) External view of the Basilica and (right) the interior of the dome.

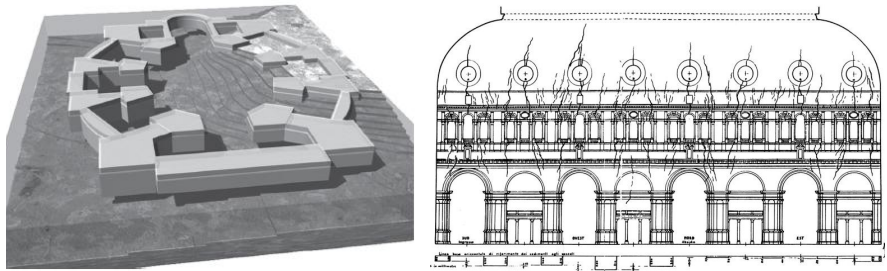


Fig. 21 (left) Axonometric view of the foundations evidencing the inclined marlstone bed-rock (dark grey) reached by the foundations of the Basilica only in the north-east part, and (right) cracking pattern of the dome and the drum recorded before the strengthening intervention (planar representation of whole perimeter of the dome, from South at left, to West, North and East at right).

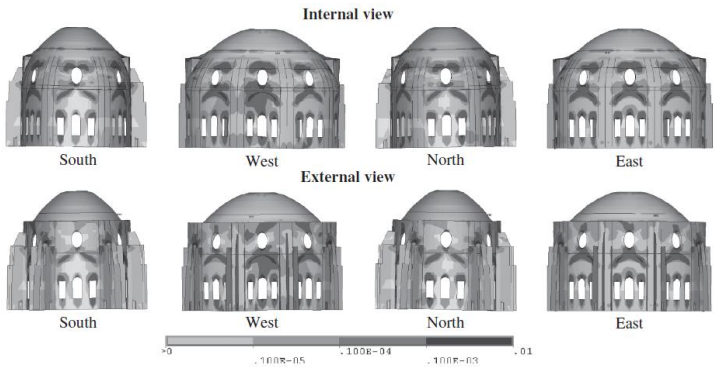


Fig. 22. Non-linear analysis under gravity loads with settlements; principal inelastic strains.

Limit analysis of the dome-drum system under gravity loads

Plastic limit analysis provides a conceptually simple and robust method to estimate the safety of masonry structures introducing the simplifying assumption that considers masonry as a rigid material with no resistance to tensile stresses and adopting the static and/or kinematic approach based on the use, respectively, of the static or kinematic theorems. As such, it has been long applied to the two-dimensional analysis of masonry structures or structural elements for expeditious evaluations of safety levels (see Section 1).

A concise approximate estimation of the safety conditions of the dome-drum system of the Sanctuary of Vicoforte under gravity loads was performed according to these procedures, applying both the static and kinematic approach to investigate, within an ideal planar problem, the stability of the masonry slices (as defined above and corresponding to an assumption of full cracking of the dome-drum system along its meridian planes) located along the major and minor axis⁵¹. Both approaches demonstrate the lack of stability of the dome-drum system in the absence of circular tension stiffening, confirming the central role conferred to the original iron rings to guarantee this stability, and prompting a positive evaluation of the strengthening intervention

input and structural modeling of the «Regina Montis Regalis» Basilica and large elliptical dome at Vicoforte, northern Italy, in J. Jasieńko (ed.), SAHC 2012, 8th International Conference on Structural Analysis of Historical Constructions, Wrocław, Poland, October 15-17, 2012, DWE, Wrocław 2012, pp. 1432-1440; G. Ventura, M. Coppola, C. Calderini, M.A. Chiorino, *Three-Dimensional Limit Analysis of the Vicoforte Elliptical Dome*, in «International Journal of Architectural Heritage: Conservation, Analysis, and Restoration», Vol. 8, N° 5, 2014, pp. 649-669; C. Casalegno, R. Ceravolo, M.A. Chiorino, M.L. Pecorelli, L. Zanotti Fragonara, *Soil-Structure Modeling and Updating of the «Regina Monte Regalis» Basilica at Vicoforte, Italy*, in F. Peña, M. Chávez (Eds.), SAHC 2014, 9th International Conference on Structural Analysis of Historical Constructions, Mexico City, Mexico, 14-17, October 2014; R. Ceravolo, G. De Lucia, M. Pecorelli, L. Zanotti Fragonara, *Monitoring of historical buildings: Project of a dynamic monitoring system for the world's largest elliptical dome*, IEEE Workshop on Environmental, Energy, and Structural Monitoring Systems (EESMS), Trento, Italy, 2015; R. Ceravolo, A. De Marinis, M.L. Pecorelli, L. Zanotti Fragonara, *Monitoring of masonry historical constructions: 10 years of static monitoring of the world's largest oval dome*, in «Structural Control and Health Monitoring», N. 10, 2017; G. Coletta, G. Miraglia, M. Pecorelli, R. Ceravolo, E. Cross, C. Surace, K. Worden, *Use of the cointegration strategies to remove environmental effects from data acquired on historical buildings*, in «Engineering Structures», N. 183, 2019.

⁵¹ A. Reffo, *Applicazioni dell'analisi limite alla verifica delle grandi cupole in muratura: la cupola del Santuario di Vicoforte* (Application of limit analysis to the reliability assessments of large masonry domes: the dome of the Sanctuary of Vicoforte; in Italian), School of Architecture, Politecnico di Torino Master's thesis, 2002; M.A. Chiorino, A. Spadafora, C. Calderini, S. Lagomarsino, *Modeling strategies for the world's largest elliptical dome at Vicoforte*, cit.

performed in 1985-1987 through the application of the high strength tensioned steel tie-bars, and of their subsequent re-tensioning operated in 1997, as appropriate safeguard measures. The stabilizing contribution of the original iron tension rings was taken into account in the safety evaluations on the basis of the kinematic approach – in which safety is evaluated in terms of the absolute value ratio between resisting and pushing virtual works Wr and Wp – introducing the assumption of complete plasticization of the rings, so that each point of the rings is considered subjected to a tensile stress equal to the iron yielding strength, and adding the plastic dissipation work of the rings to the sum of the resisting works Wr .

A kinematic limit analysis of the entire dome-drum system was also attempted considering the system subdivided into sixteen separate interacting slices⁵². The safety factors Wr/Wp were first determined for each separate slice as functions of the position (vertical angle α) of the intermediate hinge of their respective collapse mechanisms, adopting the same procedures as above, and without considering, in a first step, the stabilizing contribution of the original tension rings. In this case stability was found, for each one of the four symmetric sectors of the dome, only for the two intermediate slices benefiting of the stabilizing contribution of external buttresses, while the lack of stability was confirmed for the two slices corresponding to the maximum and minimum diameters of the dome.

A tentative approximate evaluation of the global safety factor of the dome-drum system considered as a spatial structure – with account for the interaction between the sixteen separate slices (four slices for each sector), while still ignoring the contribution of the tension rings – was then performed. This was done by adding, for each one of the four symmetric sectors of the dome-drum system, the contributions of each slice to Wr and Wp , and then determining the minimum value of the ratio between these sums as a function of four variables (the positions α of the intermediate hinge for each slice), obtaining an approximate global safety estimation for the entire dome-drum system (Wr/Wp)_{dome-drum} = 1.27.

Finally, the stability of the dome was analyzed considering the contribution of the original iron tension rings by adding, as previously indicated, the plastic dissipation work of the rings to the sum of the resisting works Wr . Significant increases in the safety coefficients were consequently obtained, both in the verification of the stability of the single slices, confirming the result trends of the above mentioned previous evaluations, and in the estimation of the global

⁵² G. Ventura, M. Coppola, C. Calderini, M.A. Chiorino, *Three-Dimensional Limit Analysis of the Vicoforte Elliptical Dome*, cit.

safety of the dome-drum system, obtaining an approximate indicative evaluation of the global safety coefficient $(Wr/Wp)_{\text{dome-drum}} = 3.03$.

Further controls were then performed to ensure that the three tension rings, located at different levels, can exhibit simultaneously plastic dissipation work for the assumed mechanisms, checking that the difference between the maximum and minimum strain in the three rings is less than the extension of the plastic plateau being assumed for the iron material⁵³, and attention was paid also to the influence of possible non-uniform strain and stress distribution along the iron rings, due to friction and adherence to the masonry.

A lower indicative value of the global safety coefficient $(Wr/Wp)_{\text{dome-drum}} = 2.08$ is obtained if reference is made to the more restrictive assumption of not taking advantage of the plastic resources of the iron tension rings and the ratio between resisting and pushing works is evaluated for a deformed configuration of the collapse mechanism that brings the most strained ring at initial yielding.

In what concerns the results of all above mentioned evaluations, attention should be paid more to the order of magnitude and general trends of safety levels, than to specific values of safety coefficients, as determined in particular e.g. through the kinematic approach. These values may in fact be debatable, as they depend, among other things, on the way in which – in the definition of the reference ideal planar slices adopted in the computational procedures – the presence of window openings is accounted for, on the simplified assumptions introduced to account for the interaction between the separate slices in the approximate evaluation of the global safety factor of the dome-drum system considered as a spatial structure, and on the perhaps too schematic and non conservative assumption introduced for the restraint conditions at the base dome-drum system (a fixed hinge, without horizontal displacements) to model the effective, although significant, containing action exerted by the underlying parts of the monumental structure.

Non-linear FEM analyses with shell elements of the dome-drum system under gravity loads and with account for settlements

This approach, aimed at a more refined and realistic analysis of the mechanical response of the dome-drum system and at an interpretation of its historical damage prior to the strengthening intervention, incorporates within a finite element method (FEM) analysis a non-linear anisotropic damage constitutive model for the masonry capturing the principal non linear aspects of its behaviour⁵⁴. This

⁵³ Experimental checks in terms of stress-strain diagrams on the original iron material still to be performed. Refer to the original paper for further details.

⁵⁴ C. Calderini, S. Lagomarsino, *A continuum model for in-plane anisotropic inelastic behaviour of masonry*, in «Journal of Structural Engineering», 134/2, 2008, pp. 209-220.

constitutive model, which considers the different in-plane damage mechanisms affecting both the mortar joints and the blocks (both friction and cohesive mechanisms), was implemented in non-linear 4-node shell elements with transverse shear strain capability. The constitutive equations were implemented in a general-purpose finite element code⁵⁵. The original iron rings are modelled by nonlinear link elements for which a Von Mises strength criterion is adopted.

Two types of analysis were performed. In the first one, only the weight of the dome-drum system, plus the lantern, was considered. In the second, the effects of the differential settlements of the foundations, as determined from the optical leveling performed at the base of the drum, were also considered, and applied as vertical imposed displacements to the nodes at the base of the drum⁵⁶.

The results of this second analysis shown in Figure 22 evidence the regions of more intense masonry damage, which is responsible for the development of cracks. In particular, the west side of the dome-drum system, characterized by higher values of the differential settlements, appears more damaged than the east side, which corresponds to the cracking pattern recorded before the strengthening intervention (Fig. 21 right).

Based on the same computational instrument incorporating the non-linear anisotropic damage constitutive model for the masonry, an incremental FEM analysis under gravity loads was also performed⁵⁷ for estimating the multiplier of the self weight at collapse, for the sake of comparison to the results, in terms of safety levels, obtained through the limit analysis approaches described in the preceding section. As expected, further larger values of the safety margins were detected⁵⁸, with respect also to the evaluations based on the global kinematic limit analyses of the entire dome-drum system. This confirms that the simplest two dimensional limit analyses performed on single slices of the dome-drum system give in any case conservative safety evaluation results

⁵⁵ ANSYS 2003.

⁵⁶ M.A. Chiorino, A. Spadafora, C. Calderini, S. Lagomarsino, *Modeling strategies for the world's largest elliptical dome at Vicoforte*, cit.; M.A. Chiorino, C. Casalegno, *Survey and structural modeling for the reliability assessment of the world's largest elliptical dome at Vicoforte*, cit.

⁵⁷ G. Ventura, M. Coppola, C. Calderini, M.A. Chiorino, *Three-Dimensional Limit Analysis of the Vicoforte Elliptical Dome*, cit.

⁵⁸ Different from the assumption adopted in the limit analysis approach discussed in the preceding section, two different assumptions were introduced in what concerns the restraint conditions at the base of the drum, i.e. a) free horizontal displacements of all nodes at the base, and b) inhibited horizontal displacements. This second assumption, for which higher values of the multiplier of the self weight at collapse were detected, is presumably closer to reality by considering the stiffness of the underlying structures.

compared to all other more refined approaches, providing the lowest values for the estimated safety margins.

Therefore, even if accurate modelling procedures by most recent techniques appear as valuable tools for more refined evaluations of the safety margins, intended also to contribute to develop proper rehabilitation strategies aiming at limiting at best any possible required intervention on the architectural heritage, the simplest stages of limit analysis methodology discussed in the previous section seem to be able of giving useful first indicative conservative estimates of the global safety coefficient of a complex monumental structure like the dome-drum system of the Basilica.

Evaluation of seismic risk

Although Vicoforte is located in an area of moderate seismicity with respect to the whole Italian region (third level out of four groups ordered according to decreasing intensity), albeit not far from more active areas, the seismic risk of the Basilica deserves to be accurately investigated, and, where needed, proper strategies should be explored for its possible reduction.

This is due to the consideration, on one side, of the great historical, architectural and structural significance of the monument, and, on the other side, of its apparent vulnerability to seismic excitations, related in particular to the daring configuration of its dome-drum structural system. In fact, while these macro-elements are characterized in general by a high seismic vulnerability, as demonstrated by relevant damage or full destruction suffered in many cases on the occasion of significant seismic events in past and recent years (with special regards to Italy and its important architectural heritage of religious buildings), in the specific case of this important monument the very special configuration of its slender and transparent dome-drum system magnifies this vulnerability.

A further consideration concerns the influence on the seismic response of the unfavourable geotechnical situation of the specific site, with special regard to possible amplification effects on the seismic input induced by the soft subsoil layers.

The first steps of this new investigation and research process regarded the definition of the seismic input at the site where the Basilica is located and the dynamic characterization of the structure. Work is still in progress in what concerns the use of these results in the subsequent phases of structural dynamic analysis of the monument, and of evaluation and, the case being, mitigation of its seismic risk.

1) Definition of seismic input at the base of the monument

The research was articulated in two phases. The first phase was devoted to the

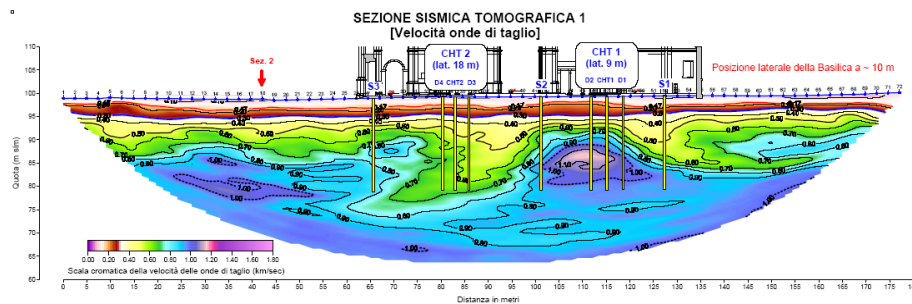


Fig. 23. Seismic tomography for S-waves carried out at the site of the Basilica at Vicoforte.

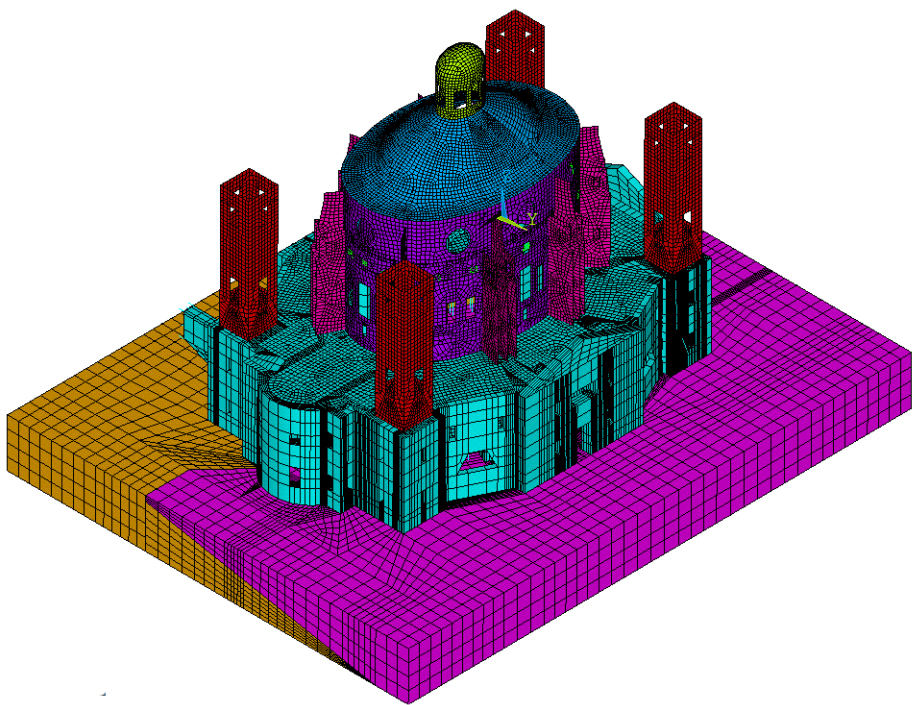


Fig. 24. The finite element model inclusive of the foundation soil layers (clay-silt in purple and marlstone in light brown). The other colours identify the different material used for the different macro-elements within the model of the structure of the Basilica.

execution of the site-specific Probabilistic Seismic Hazard Analysis (PSHA) and the Deterministic Seismic Hazard Analysis (DSHA), both under the assumption of stiff ground and level topographic condition. The DSHA was adopted to define the worst shaking scenario which would occur in the future, compatibly with the tectonic and seismic setting of the region. The probabilistic approach provided more severe ground shaking scenarios with respect to deterministic methods. Nevertheless, PSHA and DSHA are both important as they provide complementary information to the predicted hazard.

The second part of the research treated the investigation of the seismic site response through 1D stochastic and 2D deterministic approach, in order to evaluate possible amplification effects due to localized lithostratigraphic characteristics at the site. To this aim, a 3D subsoil model was constructed integrating the results of advanced geotechnical investigation campaigns including seismic tomography (Fig. 23). Finally, as an output of the study, dynamic impedances at the foundations of the Basilica were computed to be used in soil structure interaction analysis⁵⁹.

2) Dynamic characterization of the structure

The characterization of dynamic behaviour is an essential part of structural monitoring and damage control, especially in the case of complex monumental masonry buildings. Although they cannot be directly correlated with a specific safety level, dynamic investigations contribute to the updating of valid models for the reliability assessment stage of these types of structures and the optimization of prospective strengthening interventions, and they are indispensable instruments for the formulation of accurate forecasts as to their seismic behaviour.

A data acquisition campaign was performed in 2008 using tri-axial geophones and piezoelectric accelerometers. Instruments were positioned according to different acquisition setups and different sampling frequencies were used in order to arrive at a global identification of the structure. Wind, vehicle traffic and bells served as sources of excitation.

The next step was a model updating and identification process assisted by a finite element model constructed using the ANSYS computation code. In a first stage, the structure of the monument was assumed to be clamped at the base, disregarding soil-structure interaction⁶⁰. In a second stage, this aspect

⁵⁹ C.G. Lai, M. Corigliano, H. Sánchez, L. Scandella, *Definition of seismic input at the «Regina Montis Regalis» Basilica of Vicoforte, Northern Italy*, cit.; L. Scandella, C.G. Lai, D. Spallarossa, M. Corigliano, *Ground shaking scenarios at the town of Vicoforte, Italy*, cit.

⁶⁰ M.A. Chiorino, R. Ceravolo, A. Spadafora, L. Zanotti Fragonara, G. Abbiati, *Dynamic Characterization of Complex Masonry Structures: The Sanctuary of Vicoforte*, cit; M.A.

was given proper attention incorporating in the finite element model the foundation soil layers and the foundation structures of the monumental building (Fig. 24). In this case, the dynamic characterisation of the building allowed the identification and classification of 10 vibration modes and the calibration of a FE model that takes into account soil-structure interaction and dynamic effects⁶¹.

Conclusions

The lecture discussed the significant and progressively increasing role of structural and geotechnical disciplines in the strategies for conservation and rehabilitation of architectural heritage, analyzing first the gradual recognition of this role within principles and guidelines incorporated in charters and documents formulated at national and international level, in particular in recent years.

Specific attention was then paid to the contribution of these disciplines to the analyses of historical constructions and monumental buildings in the static domain for reliability assessments under gravity loads, as well as to the analyses in the dynamic domain for both model updating processes and the evaluation of the seismic risk.

Reference was made to a wide series of case studies, principally of historical architecture, with a special and more extended attention to the case study of the Santuario di Vicoforte, a monumental building of great historical, architectural, and structural significance, characterized by one of the largest masonry domes in the world, and by far the largest oval one. The lecture presented the results, at the date, of a wide investigation and research program, intended to propose the case study of Vicoforte as a reference case at national and international level for the structural conservation of important monuments, with specific attention to their protection from seismic hazards.

Reference was also made to one eminent example of contemporary structural architecture, the Hall B of the Turin Exhibition Center by Pier Luigi Nervi.

Acknowledgments

The author is particularly grateful to the research group of Dynamics and Seismic Engineering of the Department of Structural, Geotechnical

Chiorino, R. Ceravolo, C.G. Lai, C. Casalegno, *Survey, seismic input and structural modeling of the «Regina Montis Regalis» Basilica...*, cit.

⁶¹ C. Casalegno, R. Ceravolo, M.A. Chiorino, M.L. Pecorelli, L. Zanotti Fragonara, *Soil-Structure Modeling and Updating of the «Regina Monte Regalis» Basilica at Vicoforte, Italy*, cit.

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The author is also grateful, for the information provided for these and the other case studies discussed in the lecture, to his colleagues of Politecnico di Torino: Paolo Napoli, Vittorio Nascé, Giulio Ventura, and Michele Jamiołkowski (National Member of the Turin Academy of Sciences), of the University of Pavia: Carlo Lai and Giorgio Macchi (National Member of the Turin Academy of Sciences), of the University of Genoa: Sergio Lagomarsino and Chiara Calderini, and to Takayoshi Aoki of Nagoya City University and Luca Zanotti Fragonara, formerly of Politecnico di Torino and currently Cranfield University.

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Part of the text of this lecture is based on a previous paper by the author dedicated to the single case study of the Sanctuary of Vicoforte⁶², updated and significantly extended to include also the other case studies.

This opening lecture of the Academic Year of the Academy of Sciences intended to illustrate and discuss an overview of the current scenarios of advanced debate and recent progresses on the conservation of the architectural heritage in the frame of a cultural interdisciplinary vision at the interface between scientific and technical disciplines and architectural and historical culture. For any deeper insight on scientific and technical aspects reference can be made to the referenced literature. The present pdf edition contains some corrections and updates with respect to the printed edition published in Atti della Accademia delle Scienze di Torino, Classe di Scienze Fisiche, Matematiche e Naturali, Vol. 154, 2020.

⁶² M.A. Chiorino, *The role of structural engineering and geotechnics in the conservation of historical monuments. The case study of the of the Sanctuary of Vicoforte with its large elliptical dome*, in Carolina Di Biase, F. Albani (Eds.), *The Teaching of Architectural Conservation in Europe*, Maggioli Editore, Santarcangelo di Romagna (RN) 2019, pp. 203-225.